CHAPTER 20

Seismological Studies of the San Fernando Earthquake and Their Tectonic Implications[1]

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ABSTRACT

Improved hypocentral locations have been obtained for the San Fernando earthquake and its larger aftershocks through the use of data from portable stations installed in and around the aftershock area subsequent to the main shock. The main shock, at 14 00 41.8 GMT on 9 February 1971, is now assigned a magnitude (M_L) of 6.4 and a location at 34° 24.7′ N, 118° 24.0′ W, h = 8.4 km. Fifty-five aftershocks of magnitude 4.0 and greater had occurred through 31 December 1971. The lunate-shaped epicentral distribution of aftershocks is consistent with the idea of southward thrusting along a disc-shaped fault surface, and aftershock depths as well as aftershock focal mechanisms suggest that the thrust surface dips about 35° toward N 20° E. However, a distinct linear alignment of left-lateral strike-slip aftershocks parallel to the motion direction near the west boundary of activity suggests that the fault surface has a steep flexure along this line, down-stepped to the west, and both the planar distribution of aftershocks and the local geology support this concept.

The purpose of this paper is to describe the seismologic aspects of the San Fernando earthquake of 9 February 1971 and its aftershocks and to interpret these earthquakes in terms of a tectonic model of the associated faulting. Several reports on these subjects were prepared by the authors within 3 weeks following the earthquake (Allen *et al.*, 1971; Hanks *et al.*, 1971; Whitcomb, 1971; Division of Geological and Planetary Sciences, 1971), and this paper updates these studies utilizing information recorded by the Caltech network through 31 December 1971. By this time, the principal aftershock activity seems to have concluded, although small aftershocks still continue. During the seismological investigations, particular effort has been made to gain an understanding of the tectonic mechanism of the earthquake—the configuration of the fault surface, the source mechanism of the main shock and aftershocks, and the tectonic environment of the faulted region. Preliminary conclusions on these topics are summarized herein, although it should be recognized that studies are vigorously continuing, and much detailed substantiating evidence as well as possible modifications will be presented in subsequent papers.

SEISMOLOGIC ENVIRONMENT

In the years prior to 1971, the San Fernando area was characterized by low to moderate seismic activity not unlike that of many other parts of southern California. Indeed, the 1934–1963 strain-release maps (Allen *et al.*, 1965) indicated that the northern San Fernando Valley was seismically less active than most other parts of the greater Los Angeles area. Nothing that has been recognized in the very recent seismic history seems to suggest that this area, more than any other area, was particularly likely to experience a magnitude 6.4 earthquake. It should be kept in mind, however, that an earthquake of at least this magnitude occurs somewhere in the southern California region on the average of about once every 4 years (Allen *et al.*, 1965), and in this sense the San Fernando earthquake was no great surprise. An earthquake of this same magnitude occurred in 1968 in the Borrego Mountain area 220 km southeast of Los Angeles, but damage was small because—unlike the 1971 event—it occurred in a remote location.

Between 1934 and 1971, which is the interval during which epicentral locations of southern California earthquakes have been listed by the California Institute of Technology, only about ten earthquakes of magnitude 3.0 and greater occurred in the area that corresponds to the epicentral region of the San Fernando earthquake (Figures 1, 2). Prior to 1934, however, one earthquake is of special importance; this is the so-called Pico Canyon earthquake of 1893 (Townley and Allen, 1939), which was apparently centered only slightly west of the 1971 epicenter and was of only slightly lesser magnitude. It does indicate, significantly, that moderate earthquakes of this size were not unknown in the region.

Although most of the faults of the San Fernando area had not been generally recognized by geologists and seismologists as "active" prior to 1971, abundant unpublished evidence indicated that some were active. Particularly along the Tujunga segment of the San Fernando fault, geologists of the Metropolitan Water District had—long before the earthquake—carefully

[1] Contribution No. 2124, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena. Manuscript submitted to the California Division of Mines and Geology January 24, 1972.

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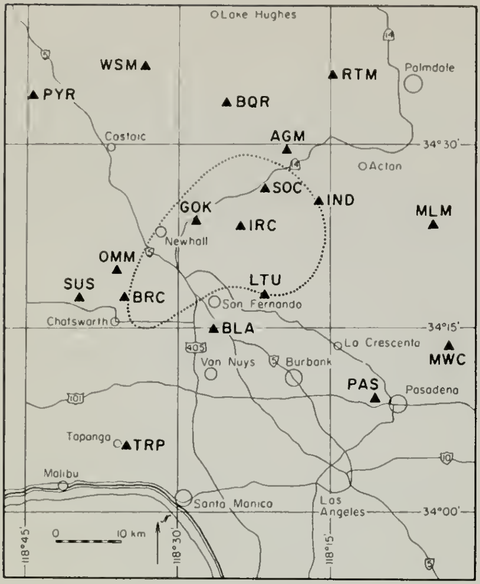

Figure 1. Aftershock area of the San Fernando earthquake (dotted line), showing locations of seismograph stations (triangles) that were used in the epicentral locations of this study. Station data are given in table 1.

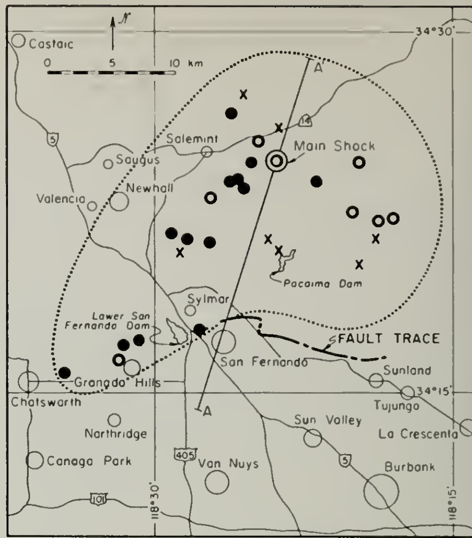

Figure 2. Earthquakes of the San Fernando series of magnitude 4.0 and greater through 31 December 1971. Solid circles represent "A" locations (see text), open circles "B" locations, and heavy X's "C" locations. Dotted line shows limits of most aftershock activity, including many smaller shocks than those shown. Cross section A–A' is shown in figure 4.

documented the thrusting of older rocks over very young gravels (Proctor *et al.*, 1972), along the same fault which broke on 9 February. On the other hand, such evidence of geologically very recent displacements is becoming more and more widespread along many faults in coastal California, and there was no known reason to have picked out the San Fernando fault more than many others as being a particularly likely candidate for an earthquake in 1971. The lesson is clear: until we gain better geologic and seismologic understanding of the relative activity of various fault zones, all of coastal California must be considered to be one of relatively high earthquake hazard.

HYPOCENTRAL LOCATIONS

In our earlier papers, Allen *et al.* (1971) summarized the seismological data of the first 3 weeks based only on the permanent stations of the Caltech network, while Hanks *et al.* (1971) located much more precisely a number of aftershocks during a particular 18-hour period on the basis of Caltech portable stations installed in the epicentral region within a few hours of the main shock. In this paper, we attempt to use data from the Caltech portable stations, in addition to those of several other agencies (table 1, figure 1) to establish correction factors to make more effective use of the more-distant permanent stations that were the only source of seismic information during the first few hours when the great bulk of aftershock activity occurred as well as later in the aftershock sequence when most of the portable stations had been removed. For the purpose of presenting a homogeneous body of data, only shocks of magnitude 4.0 and greater have been listed in table 2 and portrayed in figure 2. We feel that this listing is relatively complete even within the first few minutes following the main shock, for which we relied heavily on the low-gain (4x, 100x) instruments of the Pasadena network, as well as on the remarkable 6-minute-long accelerograph record from Pacoima Dam (Trifunac and Hudson, 1971).

Twenty-two aftershocks of magnitude 3.5 and greater that were particularly well located by the portable stations were used to establish correction factors for the more-distant permanent stations. In general, the portable stations that were used included most of the CIT and EML stations (table 1), as well as the three USGS indicated stations for a more limited number of shocks. Although the more-distant stations of the Caltech network (those indicated by an asterisk in table 1) were not used in the precise locations, time residuals at these stations were calculated in each case, and the average travel-time correction factors thus obtained for these and the other permanent stations are as follows:

PAS	+.2 sec
MWC	—.1
PYR	—.2

Table 1. Seismographic stations whose data were used in epicentral locations shown on figure 2 and in table 2. Stations indicated by asterisks are distant stations used only for locations of shocks during first few hours, before temporary stations were established. Agency designations are: CIT, California Institute of Technology; DWR, California Department of Water Resources; EML, Earthquake Mechanism Laboratory of NOAA; UCSD, University of California at San Diego; USGS, National Center for Earthquake Research of the U.S. Geological Survey. Distance is that to hypocenter of main shock.

Station		Agency	North Latitude	West Longitude	Distance (km)	Period of operation
AGM	Agua Dulce	EML	34 29.5	118 19.3	14.7	2/10–4/24
BLA	Blayney	CIT	34 18.8	118 26.7	20.6	3/02–present
BQR	Bouquet Canyon	CIT	34 33.5	118 25.5	18.9	2/09–5/07
BRC	Brown's Canyon	CIT	34 17.6	118 35.4	23.5	2/09–5/07
CSP*	Cedar Springs	DWR	34 17.9	117 21.5	97.2	permanent
GOK	Golden Oak Ranch	CIT	34 23.1	118 28.3	11.4	2/10–5/06
GSC*	Goldstone	CIT	35 18.1	116 48.3	176.1	permanent
IND	Indian Canyon	CIT	34 25.2	118 16.2	15.2	2/10–4/22
IRC	Iron Canyon	CIT	34 23.3	118 23.9	9.3	2/09–5/07
ISA*	Isabella	CIT	35 38.6	118 28.6	139.0	permanent
LTU	Little Tujunga	UCSD	34 17.7	118 21.6	16.0	2/09–2/11
MLM	Mill Creek Summit	EML	34 23.4	118 04.8	31.2	2/10–4/24
MWC	Mount Wilson	CIT	34 13.4	118 03.5	39.1	permanent
OMM	Oat Mountain	EML	34 19.8	118 36.0	22.5	2/25–4/22
PAS	Pasadena	CIT	34 08.9	118 10.3	37.0	permanent
PLM*	Palomar	CIT	33 21.2	116 51.7	184.5	permanent
PYR	Pyramid	DWR	34 34.1	118 44.5	37.1	permanent
RTM	Ritter Ranch	EML	34 35.8	118 14.8	26.7	2/10–4/22
RVR*	Riverside	CIT	33 59.6	117 22.5	105.6	permanent
SBLG	Laguna Peak	USGS	34 06.6	119 03.9	70.2	permanent
SOC	Soledad Canyon	CIT	34 26.1	118 21.7	10.0	2/10–5/06
SUS	White Oaks Park	USGS	34 17.3	118 39.8	29.0	2/12–4/24
SYP*	Santa Ynez Peak	CIT	34 31.6	119 58.7	145.5	permanent
TRP	Trippet Ranch	USGS	34 05.4	118 35.1	40.4	2/12–4/24
WSM	Warm Springs	EML	34 36.4	118 33.5	27.6	2/10–4/24

SYP	+.6
ISA	+.5
GSC	+.2
CSP	+.1
PLM	+1.3

In addition, correction factors were applied to some of the portable stations in the southwestern part of the aftershock region, where considerable thicknesses of alluvium and sedimentary rocks are locally present, as contrasted to the basement rocks that closely underlie most of the rest of the area. These correction factors, based on the local geology, were: BLA, —.5; BRC, —.3; OMM, —.3; SUS, —.2; LTU, —.2 sec. All of the above travel-time correction factors were applied to a computer-location program based on the three-layer southern California crustal model of Press (1960). In actuality, this model is clearly a gross oversimplification; in their explosion calibration of the US Geological Survey network in this same area, Wesson and Gibbs (1971) demonstrated that the local geology and crustal structure are very complicated and variable.

One effect of using both the travel-time correction factors and the larger number of close-in stations has been to assign generally shallower hypocentral depths than those obtained earlier. Thus, for example, the hypocenter of the main shock is now assigned a depth of 8.4 km (table 2) instead of the earlier 13.0 km (Allen *et al.*, 1971), although the effect on the location of the epicenter is less than 1 km.

Hypocenters obtained in this study have been divided into three categories of accuracy (table 2), depending on the number and location of stations used in the solution and on the standard error of the computer solution. We feel that "A"-quality locations are generally accurate to within 2 km horizontally and 4 km vertically. "B"-quality hypocenters are felt to be accurate to within 4 km horizontally and 8 km vertically; and "C"-quality solutions are still less accurate. Those hypocentral locations in the vicinity of the main shock probably are much better than these standards, and the depths of the deeper shocks are more accurately determined than those of shallow focus. The figures represent somewhat subjective but conservative judgments based on attempts at location under a wide variety of assumptions, as well as on the comparison of some of our solutions with the largely independent US Geological Survey solutions based on explosion calibration (R. Wesson, personal communication).

Because of the difficulty in obtaining hypocentral solutions for the numerous large aftershocks that occurred within the first 10 minutes following the main shock (table 2), it is dangerous to attempt to draw conclusions about possible migrations in aftershock activity with time. It nevertheless may be significant that all of the larger aftershocks that we have located in the southwestern extremity of the aftershock zone —near Chatsworth and Granada Hills (figure 2)— occurred relatively late in the aftershock period. The largest flurry of activity started almost 2 months after the main shock and included the shallow magnitude

Table 2. Shocks of the San Fernando series of magnitude 4.0 and greater, 9 February 1971 through 31 December 1971. For meaning of "Quality" see text.

Date	Time (GCT)	North latitude	West longitude	Depth (km)	Quality	Magnitude
2 09	14 00 41.8	34 24.7	118 24.0	8.4	B	6.4
2 09	14 01 08					5.8
2 09	14 01 33					4.2
2 09	14 01 40					4.1
2 09	14 01 50					4.5
2 09	14 01 54					4.2
2 09	14 01 59					4.1
2 09	14.02 03					4.1
2 09	14.02 30					4.3
2 09	14 02 31					4.7
2 09	14 02 44					5.8
2 09	14 03 25					4.4
2 09	14 03 46					4.1
2 09	14 04 07					4.1
2 09	14 04 34					4.2
2 09	14 04 39					4.1
2 09	14 04 44					4.1
2 09	14 04 46					4.2
2 09	14 05 41					4.1
2 09	14 05 50					4.1
2 09	14 07 10					4.0
2 09	14 07 30					4.0
2 09	14 07 45					4.5
2 09	14 08 40					4.0
2 09	14 08 07					4.2
2 09	14 08 38					4.5
2 09	14 08 53					4.6
2 09	14 10 21.5	34 21.3	118 19.0	−2.0	C	4.7
2 09	14 10 28					5.3
2 09	14 16 12.9	34 20.3	118 19.9	11.1	C	4.1
2 09	14 19 50.4	34 21.4	118 24.4	11.8	C	4.0
2 09	14 34 36.1					4.9
2 09	14 39 17.7	34 20.9	118 23.9	7.0	C	4.0
2 09	14 40 17.4	34 26.0	118 23.9	−2.0	C	4.1
2 09	14 43 47.5	34 20.8	118 28.9	5.9	C	5.2
2 09	15 58 20.9	34 22.5	118 20.1	9.0	B	4.8
2 09	16 19 26.5	34 27.4	118 25.6	−1.0	C	4.2
2 10	03 12 12.0	34 22.2	118 18.1	.8	B	4.0
2 10	05 06 35.7	34 24.7	118 19.8	4.7	B	4.3
2 10	05 18 07.2	34 25.5	118 24.9	5.8	B	4.5
2 10	11 31 34.6	34 23.1	118 27.3	6.0	B	4.2
2 10	13 49 53.7	34 23.9	118 25.1	9.7	A	4.3
2 10	14 35 26.7	34 21.7	118 29.2	4.4	A	4.2
2 10	17 38 55.1	34 23.8	118 22.0	6.2	A	4.2
2 10	18 54 41.7	34 26.7	118 26.2	8.1	A	4.2
2 21	05 50 52.6	34 23.8	118 26.3	6.9	A	4.7
2 21	07 15 11.8	34 23.5	118 25.6	7.2	A	4.5
3 07	01 33 40.5	34 21.2	118 27.4	3.3	A	4.5
3 25	22 54 09.9	34 21.4	118 28.5	4.6	A	4.2
3 30	08 54 43.3	34 17.7	118 27.8	2.6	A	4.1
3 31	14 52 22.5	34 17.2	118 30.9	2.1	A	4.6
4 01	15 03 03.8	34 24.7	118 25.2	7.1	A	4.2
4 02	05 40 25.1	34 17.0	118 31.7	3.0	A	4.0
4 15	11 14 32.0	34 15.9	118 34.6	4.2	A	4.2
4 25	14 48 06.5	34 22.1	118 18.9	−2.0	B	4.0
6 21	16 01 08.5	34 16.4	118 31.9	4.1	B	4.0

4.6 shock of 31 March that locally caused more damage in Granada Hills than did the main shock itself (Barrows *et al.*, this volume).

MAGNITUDES

The local magnitude (M_L) of the San Fernando earthquake main shock was tentatively given as 6.6 by Allen *et al.* (1971) and Division of Geological and Planetary Sciences (1971) on the basis of initial examination of the low-gain (4x) Wood-Anderson NS seismogram written at Pasadena. Subsequently, other low-gain instrumental records of the Pasadena network have been examined in detail, and we herein update our original estimate of M_L on the basis of records from Riverside, Cottonwood, and Santa Barbara, in addition to Pasadena. All normal-magnification (2800) Wood-Anderson instruments were off-scale, such as those at Barrett and Tinemaha. Resulting magnitude assignments from the various low-gain instruments are as follows:

Pasadena	NS	4x	$M_L = 6.7$
Riverside	NS	4x	6.5
Santa Barbara	EW	100x	6.3
Cottonwood	NS	100x	6.3
Cottonwood	EW	100x	6.3

The Pasadena determination is subject to the additional uncertainty that the $-\log A_0$ correction (Richter, 1958) is a very sensitive function of distance for epicentral distances of less than 50 km.

On the basis of these determinations, we assign $M_L = 6.4$ to the San Fernando earthquake. This compares closely to the mean magnitude of 6.48 assigned by Bolt and Gopalakrishnan (this volume) from four stations of the Berkeley network. The PDE listing by the National Earthquake Information Center of NOAA is $M_S = 6.2$, $m_b = 6.5$, based on 279 stations reporting.

Magnitudes have been assigned to aftershocks (table 2) on the basis of readings from eleven standard Wood-Anderson torsion seismometers at six widely spaced stations of the southern California network (Pasadena, Barrett, Cottonwood, Riverside, Santa Barbara, Tinemaha). Most magnitudes have been determined by averaging the readings from at least five of these stations. It is significant, however, that the average standard deviation for individual station readings for 20 aftershocks of magnitude 4.0 and greater, each recorded at five or more stations, was 0.30. Considering this large variation observed on standard instruments in a wide variety of azimuths from the epicenter, some of the discrepancies between Caltech and Berkeley magnitudes reported by Bolt and Gopalakrishnan (this volume) are not surprising.

FOCAL MECHANISMS AND TECTONIC INTERPRETATIONS

Fault-plane solutions for the main shock have been carried out independently by several investigators (Canitez and Toksoz, in press; Dillinger and Espinosa, 1971; Wesson *et al.*, 1971; Whitcomb, 1971a), and they agree that the basic mechanism of initial faulting was that of a thrust striking about N 70° W, dipping about 50° NE, and including a significant component of left-lateral slip in addition to the thrust component. This agrees remarkably well with the surface observations of faulting in the Sylmar-San Fernando area, some 13 km farther south. Kamb *et al.* (1971), for example, report the overall trend of the surficial fault break to be N 72° W with north dips averaging about 42°; they also report "nearly equal amounts of north-south compression, vertical uplift

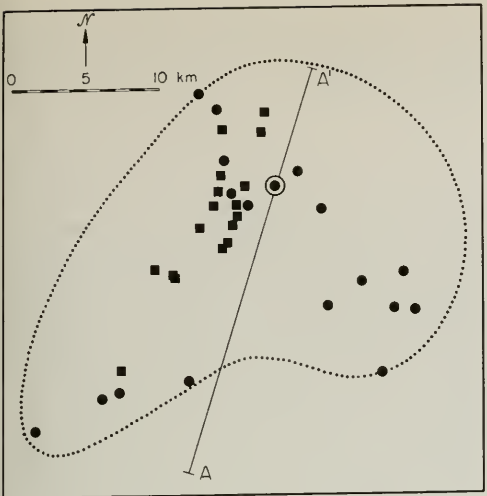

Figure 3. Earthquakes of "A" and "B" hypocentral accuracy (see text) for which good fault-plane solutions have been obtained indicating either left-lateral strike slip on north-striking planes (squares) or thrusting on north-dipping planes (circles). A number of epicenters are shown here that are not on figure 2 because some earthquakes down to magnitude 3.0 have been included. Dotted line is same as in figures 1 and 2.

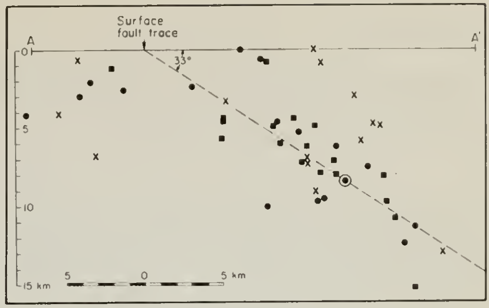

Figure 4. Vertical cross section along line A–A' of figures 2 and 3, with hypocenters projected into the plane of section. Symbols are the same as in figure 3, except that additional small crosses indicate well located earthquakes for which ambiguous or transitional fault-plane solutions have been obtained.

(north side up), and left-lateral slip."

The hypocentral locations of the main shock and aftershocks presented herein support the idea of displacement on a north-dipping thrust fault, and it seems particularly likely that the lunate distribution of aftershock epicenters (figures 2, 3; Allen *et al.*, 1971; Hanks *et al.*, 1971; Wesson *et al.*, 1971) reflects the edge of the disc-shaped segment of the fault plane that slipped during the earthquake, where stresses remained high following the main shock. Very few aftershocks occurred in the vicinity of the surface break, presumably because stresses were completely relieved there. Two principal areas of interest remain: (1) aftershocks near Granada Hills and Chatsworth, at the southwest end of the aftershock zone (figure 2), are south of the projected trace of the thrust fault and therefore do not fit so simple a picture of thrusting; and (2) focal-mechanism studies of aftershocks (Whitcomb, 1971a, 1971b) include many shocks of strike-slip character that demand an explanation more complicated than that of a simple thrust surface.

Disregarding momentarily those aftershocks near Granada Hills and Chatsworth, it is clear from figure 4 that the average dip of the zone of faulting north from the fault trace is considerably less than the 50° dip indicated by the focal mechanism of the main shock. One might explain this by systematic errors in the depth assignment of the hypocenters shown in figure 4, but substantiating evidence of the relatively shallow dip of the fault zone is given by the motion vectors of individual focal-mechanism solutions. For some 65 aftershocks, the motion vectors closely concentrate around an average plunge of 36° toward N 20° E, which corresponds closely to the dip of the hypothetical fault surface passing through the hypocenter of the main shock and the main concentration of aftershock hypocenters (figure 4). We prefer to believe, therefore, that the steep dip of the fault plane portrayed by the focal mechanism of the main shock represents only the very initial motion, and that the fault displacement then propagated to the surface along a zone dipping some 15° less steeply. The focal-mechanism data on which this and the following arguments are based will be presented in detail in a separate paper by Whitcomb; the principal ideas have already been presented in Whitcomb, 1971a and 1971b.

It is clear from figure 3 that the aftershocks of dominantly strike-slip character delineate a relatively well-defined north-trending zone west of the epicenter of the main shock. If the solutions portrayed right-lateral slip, this zone might be visualized as a typical tear fault (Hills, 1963) extending toward the ground surface, but their consistent portrayal of left-lateral slip demands instead that the thrust surface turn *downward* along this zone. These strike-slip earthquakes typically occur on fault surfaces dipping steeply westward, and we thus visualize a linear, steep flexure in the fault surface along this zone (figure 5). Under this hypothesis, most of the strike-slip aftershocks should be deeper than the thrust aftershocks to the east, and this is permitted but not demanded by the data of figure 4. It is significant, however, that all but one of the few thrust-type aftershocks deeper than the main shock (figure 4) occur within and west of the flexural zone, suggesting that the flexure is in essence a north-plunging, steep-flanked monocline that simply steps down the thrust plane to a somewhat greater depth west of the flexure, perhaps by 3–5 km.

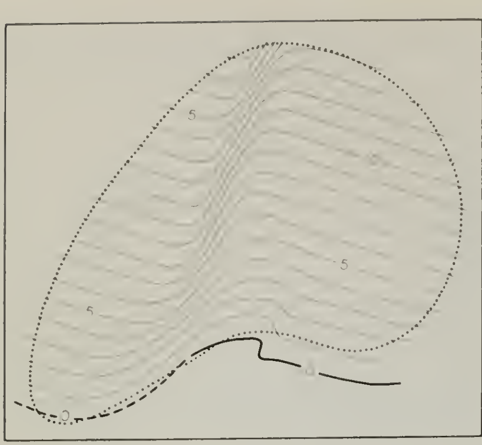

Figure 5. Schematic structural contour map showing simplified contours, in kilometers, on fault plane and showing monoclinal flexure that might explain strike-slip aftershock mechanisms on steep west-dipping flank of flexure in fault surface.

If indeed a flexure exists along the zone of strike-slip aftershocks, one geometric effect would be to displace the trace of the thrust fault to the south on the west side of the flexure (figure 5), and this may be the explanation of the aftershocks near Granada Hills and Chatsworth that are south of the trace of the fault as projected westward from the Sylmar and Tujunga segments. Furthermore, their predominant thrust-type focal mechanisms are consistent with their being west of the flexure, in analogy to those thrust-type aftershocks at the very northwest corner of the aftershock area (figure 3). It is also significant that all of the thrust-type aftershocks west of the flexure seem to have occurred well after the initiation of aftershock activity, on or after 11 February; the larger shocks in the Chatsworth-Granada Hills area (figure 2) all occurred after 30 March very late in the aftershock period.

Further support for the existence of a north-trending flexure comes from the mapped geology of the area (Wentworth and Yerkes, 1971, figure 2). The trace of the Santa Susana thrust, which lies parallel to and some 4 km north of the San Fernando fault, makes a distinct bend north of Granada Hills in exactly the manner postulated for the San Fernando fault (figure 5). Furthermore, the fact that basement rocks are widely exposed in the San Gabriel Mountains east of this zone, whereas only younger sedimentary rocks are exposed to the west, strongly supports the concept of a flexural down-step to the west in this area.

Thus we argue that the San Fernando earthquake was caused by displacement on a thrust fault or zone of thrust faults dipping about 35° north and striking about N 70° W. Particularly where the fault trace trended more westerly, as along the Sylmar segment, significant left-lateral slip occurred. A steep flexure in the thrust-fault surface, parallel to (and probably controlling) the direction of slip and down-stepped to the west, tended to limit the zone of initial breaking on the west and led to numerous aftershocks of left-lateral strike-slip character on the steep west-dipping flank of the flexure. Some thrust displacement occurred later on the down-stepped segment of the thrust fault west of the flexure, as indicated by aftershocks in the Chatsworth-Granada Hills area and in the northwestern extremity of the aftershock zone north of Solemint. Whitcomb (1971a; 1971b) has pointed out that many of the aftershocks east of the main epicenter have fault-plane solutions which are consistent with normal faulting along steep northwest-trending faults; for simplicity, such shocks have not been shown on figures 3 and 4, but these events agree with the concept of compressional release resulting from a southward thrust toward the San Fernando Valley.

ACKNOWLEDGMENTS

We are particularly indebted to many other agencies and persons for supplying data from their portable stations that have been used in our study: Earthquake Mechanisms Laboratory, NOAA (Don Tocher); National Center for Earthquake Research, USGS (Robert Wesson, Willy Lee); University of California at San Diego (James Brune); California Department of Water Resources (Paul Morrison). At Caltech, Gladys Engen, Mark Gaponoff, Jan Garmany, and John Nordquist read many of the records and carried out many of the computer solutions. This study was supported by the Caltech Earthquake Research Affiliates and by the National Science Foundation (Grant GA29920).

SAN FERNANDO, CALIFORNIA, EARTHQUAKE OF 9 FEBRUARY 1971

GORDON B. OAKESHOTT, *Editor*
CALIFORNIA DIVISION OF MINES AND GEOLOGY

BULLETIN 196
California Division of Mines and Geology
Resources Building, Sacramento, California
1975